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Title: Coastal climate is associated with elevated solar irradiance and higher serum vitamin D levels

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Abstract: Introduction
There is evidence that populations living close to the coast have improved health and wellbeing. Coastal environments are linked to promotion of physical activity through provision of safe, opportune, aesthetic and accessible spaces for recreation. Exposure to coastal environments may also reduce stress and induce positive mood. In addition to these processes we hypothesised that coastal climate may influence the vitamin D status of residents and thus partly explain benefits to health.

Materials and Methods
Ecological and cross-sectional analyses were designed to elucidate the connection between coastal residence and vitamin D status. We divided residential data, from developed land use areas and the Lower Super Output Areas of the 1958 Birth Cohort participants, into the following coastal bands: <1km, 1-5km, 5-20km, 20-50km and over 50km. In the ecological analysis we used a multiple regression model to describe the relationship between UVvitd and coastal proximity adjusted for latitude. Subsequently, using the residential information of the participants of the 1958 Birth Cohort we developed a multiple regression model to understand the relationship between serum 25(OH)D (a marker of vitamin D status) and coastal proximity adjusted for several factors related to vitamin D status (e.g. diet, outdoor activity).

Results
We found that coastal proximity was associated with solar irradiance; a 99.6 (96.1-103.3) J/m2/day regression coefficient was observed for settlements <1 km from the coast compared with those above 50 km. This relationship was modified by latitude with lower latitude exhibiting a greater effect. Individuals living in the <1 km coastal category had on average a 4 nmol/l higher vitamin D status compared to those living inland.

Conclusion

Geographic location in the UK may influence human biochemistry and health outcomes due to environmental factors. This can provide benefits in terms of vitamin D status but may also pose a risk due to higher skin cancer rates. We provide further evidence in support of the claim that coastal environments can provide opportunities for health and wellbeing.

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09 July 2014

Dear Dr Alcock,

Please find attached our manuscript entitled “Coastal climate is associated with elevated solar irradiance and higher serum vitamin D levels”, submitted for review and publication in Environment International. We believe that EI is the most appropriate destination for the article given the interdiscplinary approach taken to invesitgate the problem, which has utilised expertise in meterorology, geography, epidemiology and public health.

Previous work has acknolweged the complexity of determinants of vitamin D status. Geographic location in Britain may influence human biochemistry and health outcomes due to environmental factors. This can provide benefits in terms of vitamin D status but may also pose a risk due to higher skin cancer rates. We provide further evidence in support of the claim that coastal environments can provide opportunities for health and wellbeing.

Yours Sincerely,

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Coastal climate is associated with elevated solar irradiance and higher serum vitamin D levels

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Abstract

Introduction

There is evidence that populations living close to the coast have improved health and wellbeing. Coastal environments are linked to promotion of physical activity through provision of safe, opportune, aesthetic and accessible spaces for recreation. Exposure to coastal environments may also reduce stress and induce positive mood. In addition to these processes we hypothesised that coastal climate may influence the vitamin D status of residents and thus partly explain benefits to health.

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Geographic location in Britain may influence human biochemistry and health outcomes due to environmental factors. This can provide benefits in terms of vitamin D status but may also pose a risk due to higher skin cancer rates. We provide further evidence in support of the claim that coastal environments can provide opportunities for health and wellbeing.

Keywords: Ultraviolet radiation, Vitamin D, Coastal residence, Health

Highlights

- Ecological and cross sectional analyses were undertaken to understand the relationship between coastal residence and UVR induced vitamin D production in Britain
- Increasing proximity to coast is associated with higher solar irradiance
- Increasing proximity to coast is associated with higher vitamin D status
- Geographic location in Britain may influence biochemistry and health outcomes due to environmental factors

1. Introduction

There is evidence that populations living close to the coast have improved health and wellbeing (Wheeler et al. 2012). Results from ecological studies of small-area census (Wheeler et al. 2012) and panel data for England (White et al. 2013a) suggest that proximity to the coast is positively related to both self-reported general, and mental health. Living within 0-5 km of the coast is associated with a small but significant increase in general health ($\beta=0.039$, $p=0.028$) and mental health ($\beta=0.147$, $p=0.023$), compared to inland regions (White et al. 2013a). Examination of this phenomenon via alternate methods will allow more accurate weighting of previous findings, as well as investigate which mechanisms may explain associations.

Environmental factors are linked to promotion of physical activity through provision of safe, opportune, aesthetic and accessible spaces for recreation (Bauman et al., 2012); in Australia objectively measured factors such as residential coastal proximity have been associated with increased participation in physical activity (Bauman et al. 1999), an effect that has been recently demonstrated in England (White et al., Unpublished results). A multitude of evidence exists for an association between regular physical activity and primary and secondary prevention of several chronic diseases (Warburton 2006). Additional positive wellbeing benefits of outdoor activity include reduction of stress or attention restoration (Hartig et al. 2003), and the induction of positive mood (Thompson Coon et al. 2011), which are especially associated with leisure visits to the coast (White et al., 2013b). The proposal that living close to the coast may be associated with direct physiological effects, for instance higher vitamin D status due to higher Ultraviolet Radiation (UVR) exposure, have yet to be explored or fully elucidated. This possibility is particularly important because higher vitamin D status has been associated with a range of both physical and mental health benefits (see below) and thus could help account for some of the earlier findings.

The primary determinants of UVR reaching the Earth's surface are solar zenith angle (latitude, season and time of day), altitude, cloud cover, aerosols and surface reflectivity (Webb 2006). UVR is weighted by action spectra, i.e. specific wavelengths within UVA (320-400 nm) and UVB (290-320 nm) bands shown to be effective to induce a particular biological response, to quantify effect of exposure on health. The pre-vitamin D action spectrum, based on experiments by MacLaughlin et al., determines the relative effectiveness of specific wavelengths to induce the reaction between 7-dehydrocholesterol, found in the skin, and pre-vitamin D (MacLaughlin et al. 1982). The dose attained from weighting UVR by the pre-vitamin D action spectrum is named pre-vitamin D UV (UV_{vitd}). The conversion of pre-vitamin D to vitamin D_3 is a temperature dependent isomerisation, with 50% of UV-induced pre-vitamin D converted into vitamin D_3 (chloecalciferol) in 2.5 hours at skin temperatures of 37°C (Tian et al. 1993). Higher temperature also has an effect on behaviour with a higher propensity to participate in outdoor activity and wear less clothing (McCurdy & Graham 2003). We expected to observe higher UVR and temperature at the coast, due to the effect of topographic forcing on clouds and air pressure. The effect of UVR and temperature on an individual's vitamin D status is modified by intrinsic factors including those relating to vitamin D synthesis (outdoor activity, sun protection practices, ethnicity)(Webb 2006), metabolism (obesity, specific health conditions and medications) and diet (supplementation, fortification or oily fish intake) (Holick 2007).

Vitamin D status, as measured by 25(OH)D in serum, is related to several extraskeletal diseases that contribute to lower general health including autoimmune diseases, cardiovascular disease and certain cancers, due the ability of calcitrol (the hormonally active form) to regulate gene and enzyme expression and control anti-inflammatory signalling through its interaction with the vitamin D receptor (Holick 2004). Although clinical manifestation of these diseases often occur in later life, it is likely that environmental influences throughout life are key in the pathogenesis. Vitamin D status at age 45 has been associated with markers of respiratory illness (Berry et al. 2011). A 10 nmol/l decrease in 25(OH)D was related to an increased likelihood of seasonal infections (7%, 95%CI 3-11) and reduced forced expiratory volume in 1 second (8 ml 95%CI 3-13) (Berry et al. 2011).

Further, vitamin D status has been linked with mental health due to the presence of the vitamin D receptors in cells within the brain (Garcion et al. 2002). Better cognitive performance (Maddock 2013a) and fewer common mental disorders (Maddock 2013b) at age 50 are also associated with sufficient vitamin D status (50-80 nmol/l) at age 45. 25(OH)D has been associated with cognitive decline in a cross-sectional analysis of over 65 year olds (Llewellyn et al. 2009). Those below 30 nmol/l had a 2.28 (95%C 1.36-3.83) times higher risk of cognitive impairment, assessed by the Abbreviated Mental Test (Llewellyn et al. 2009).

In order to explore vitamin D as a potential mechanism for beneficial health effects of coastal residence, we firstly hypothesised that coastal proximity in British settlements is associated with higher ambient UV_{vitd} radiation. Furthermore, we aimed to describe the effect of residential coastal proximity on seasonally adjusted levels of 25(OH)D in a geographically dispersed British cohort.

2. Materials and methods

A two-stage design was used to understand if potential differences in 25(OH)D are due to coastal climate. We estimated the geographical variation in UV_{vitd}, cloud cover, temperature and precipitation for British settlements using meteorological data. A cross-sectional analysis of cohort participants was then used to estimate whether these factors have an impact on 25(OH)D after individual characteristics were taken into account. We estimated residential coastal proximity and used data on 25(OH)D measured in serum, controlling for factors relating to vitamin D synthesis, metabolism and diet.

2.1 Ecological Analysis

2.1.1 Settlement Data

Developed Land Use Areas (DLUAs) data that form part of the Meridian II product, available from Ordnance Survey were used to estimate ambient UV_{vitd} radiation in residential areas in Britain (Figure 1a). Briefly, the DLUA polygons are derived from combining points and lines that represent real-world geographic features (e.g. the intersection of roads), further details of the method to derive DLUAs are presented in the user guide (Ordnance Survey 2012); the dataset represents all settlements greater than 0.01 sq. km. A centroid for each DLUA was created using ArcGIS Desktop 10.0 (ESRI, Redlands, US) and a linear distance to coast approximated. Coastline was defined as the boundary between land and sea, ending where river estuaries narrow to approximately 1km. Distance to coast categories of 0-1 km, 1-5 km, 5-20 km, 20-50 km and over 50 km were chosen, *a priori,* based on existing literature (Wheeler et al. 2012). DLUA centroids were categorised into bands corresponding to the following latitude bands: below 51°N, 51-53°N, 53-55°N, 55-57°N and above 57°N.

2.1.2. Meteorological data

The UV_{vitd} data was obtained from satellite-derived (METEOSAT) retrievals modelled using information on solar zenith angle, total column ozone, cloud optical thickness, near-surface horizontal visibility, surface elevation and albedo (Verdebout 2004). The data is designed for UVR and human health studies and is weighted by the vitamin D action spectrum (Verdebout 2004). The most recent data (2002-2003) was made available to the researchers and was averaged for the time period. We generated an areal weighted mean for each DLUA based on the overlaid UV_{vitd} values.

Climate data for precipitation, temperature and cloud cover were downloaded for the period of interest (July 2002- June 2003) from the Met Office UKCP09 website as monthly ASCII files (Met Office 2014). The method for the generation for these datasets is published elsewhere (Perry & Hollis 2005). These were amalgamated for the 2002-2003 time period to generate a mean annual value. These values were linked to the DLUA units using the same procedure as for UV_{vitd}. Figure 1b shows the meteorological data used in the ecological analysis.

2.1.3. Statistical Analysis

The relationship between British settlement coastal proximity and UV_{vitd} was tested by using a multiple regression model with annual mean daily measurement of UV_{vitd} as the dependent variable and settlement distance to coast as the independent variable adjusting for latitude. Furthermore, the analysis was stratified by latitude bands due to an interaction effect being detected by a likelihood ratio test. We repeated the multiple regression for the other meteorological variables.

Figure 1a: Map of ONS generated Developed Land Use Areas

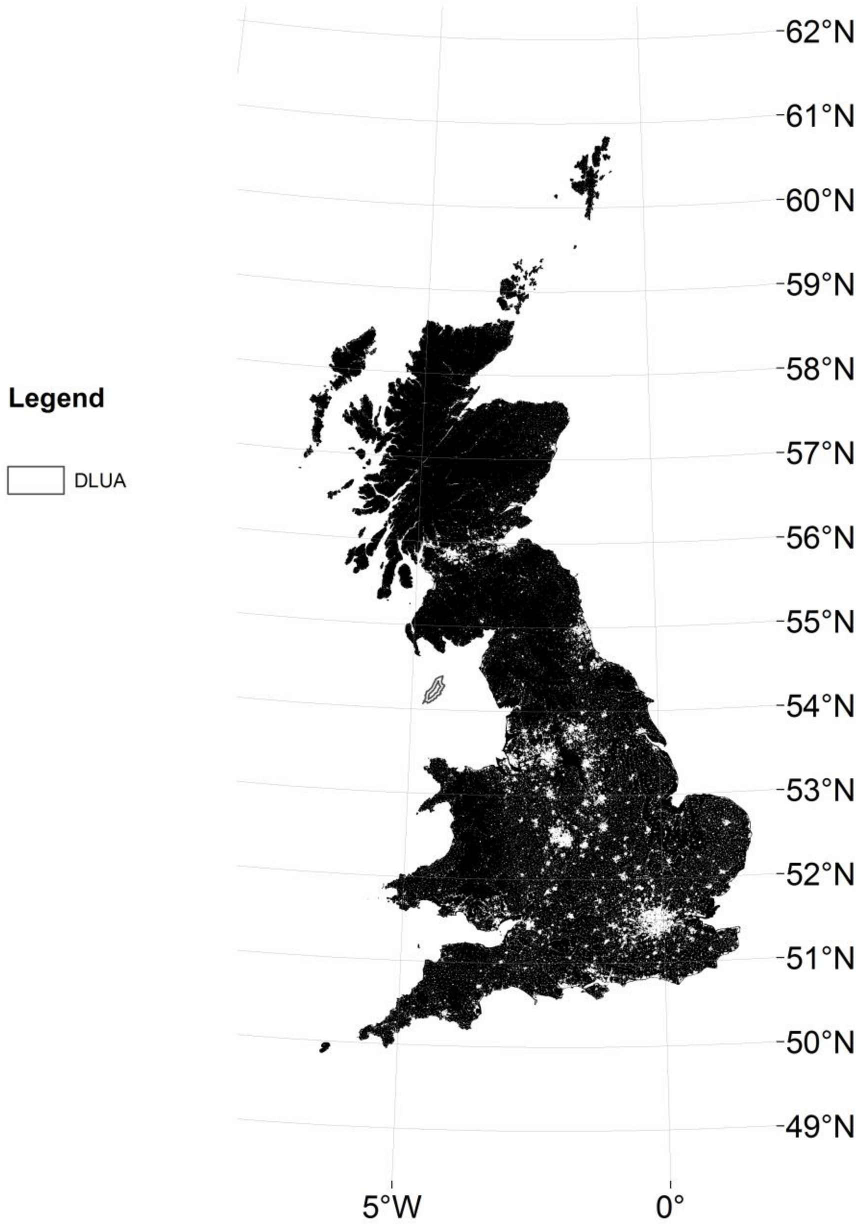
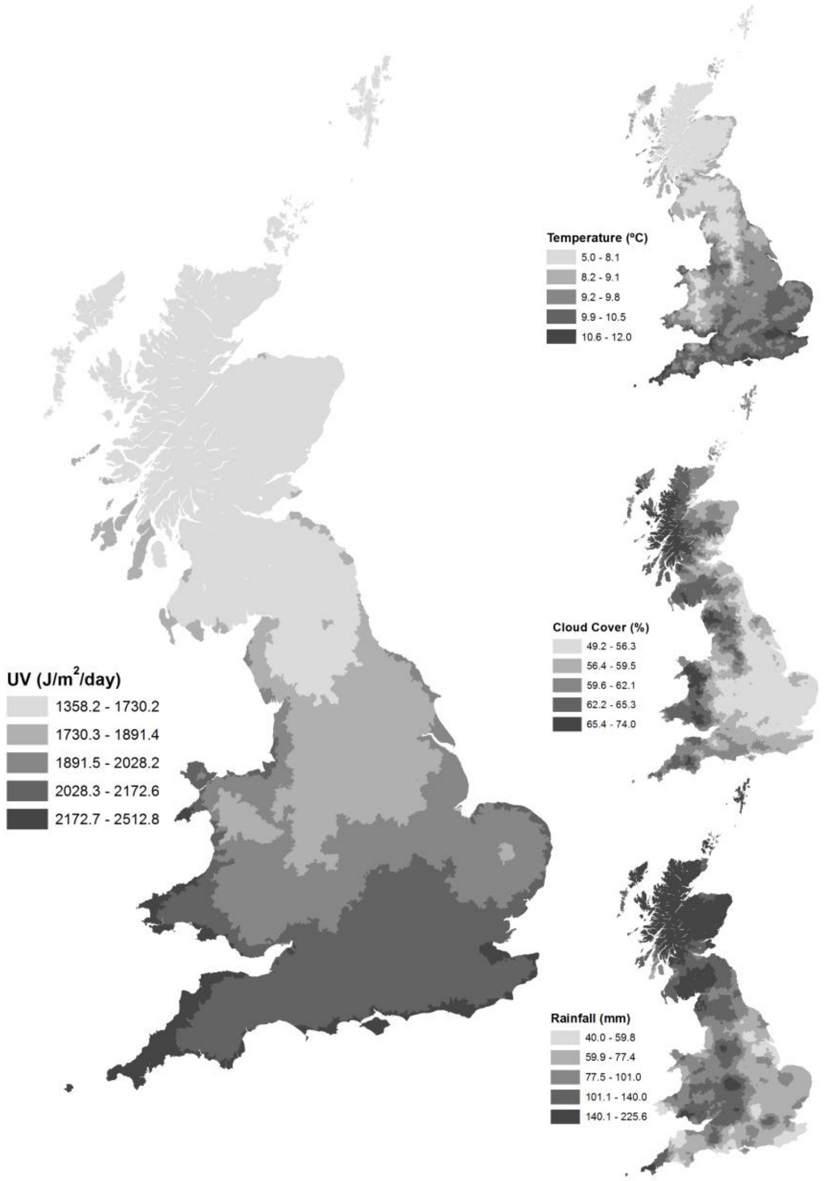


Figure 1b: Annual mean measurements of UV_{vitd}, temperature, cloud cover and rainfall: The categories are determined by Jenks natural break optimization.



2.2. Cross-sectional Analysis

2.2.1. Participants

The 1958 birth cohort is a study of 17,683 British citizens born during one week in March 1958. The cohort has been contacted at time intervals of between 4 and 10 years and detailed information collected from questionnaires on health, education and social development; a comprehensive guide to the information collected at each sweep is presented in the cohort profile (Power 2005). A sub-set of the participants still living in the United Kingdom (n=11,971/17,416; 69%), were contacted in 2002-2004, aged 45, a follow up sweep that included measurements of biomedical data. Of the 9,377 participants that completed a questionnaire: 79% had their blood taken and 92% of those had information on vitamin D status; this biomedical sweep has been shown to be largely representative of the surviving cohort (n=17,313) (Atherton et al. 2008). Cohort data included Lower-layer Super Output Area (LSOA) of residence for each participant; we generated coastal proximity measurements for each LSOA using the method outlined previously. The continuous and banded coastal proximity data were linked to the LSOA of the participant at the Centre for Longitudinal Studies, which hosts the cohort, in order to preserve anonymity and confidentiality of participant residence location. We also used questionnaire and anthropometric data relating to intrinsic characteristics and confounders, details are presented in appendix A.1. Intrinsic factors included data on summer outdoor activity and sunscreen use, which was chosen as they related to the individual's propensity to increase or decrease the ability for their skin to manufacture vitamin D when sufficient UV radiation is available. We used obesity (i.e. body mass index over 30) as a metabolic factor due to the reduction in circulating 25(OH)D due to fat sequestration (Wortsman et al. 2000). Dietary factors included vitamin D supplementation, cod liver oil supplementation and oily fish intake, which increase vitamin D status independent of UV exposure. Confounding factors included sex, social class (based on employment) and smoking status and were chosen *a priori*.

2.2.2. Statistical Analysis

To understand the relationship between coastal proximity and 25(OH)D we developed a multiple regression model using log transformed and seasonally adjusted 25(OH)D as the dependent variable and coastal proximity as the independent variable. The seasonal adjustment was undertaken using a sine-cosine model previously used by Hughes et al., (2011). This was performed on the continuous and categorised coastal proximity variable in an unadjusted and adjusted model, with the latter accounting for all *a priori* covariates.

2.2.3. Presentation of Results

The categorised results are presented with coefficients, confidence intervals, significance levels and the r^2 goodness of fit statistic. The continuous results are presented using restricted cubic splines to illustrate non-linear effects using the Stata package 'postrcspline' (Buis 2014). Five knots were used as advised when sample size is greater than 100, with position determined by Table 2.3 in Harrel (Harrell 2001). All statistical analyses were undertaken in Stata 12 (Stata Corp., College Station, US).

3. Results

3.1. Coastal Proximity and Coastal Climate

The geographical characteristics of DLUAs in Britain (n=24,238) are provided in Table 1. The majority of settlements in Britain lie within 5 and 50 km from the coast, with settlements concentrated between 51ºN and 54ºN. The mean altitude for each DLUA was 93 m with 1.5% settlements over 300 m. There was a high variation of settlement size as shown by the standard deviation of 1.08e10m in area.

Table 1: Geographic distribution of developed land use areas in Britain

Attribute	Mean ± sd or n (%)
Distance from Coast (km)	20,591 ± 20,062
>50	2,565 (11)
>20-50	7,302 (30)
>5-20	7,285 (30)
>1-5	3,773 (16)
<1	3,313 (14)
Latitude (ºN)	53 ± 2
Altitude (m)	92 ± 72
Area (m)	983,430 ± 1.08e+10
N of DLUA's	24,238

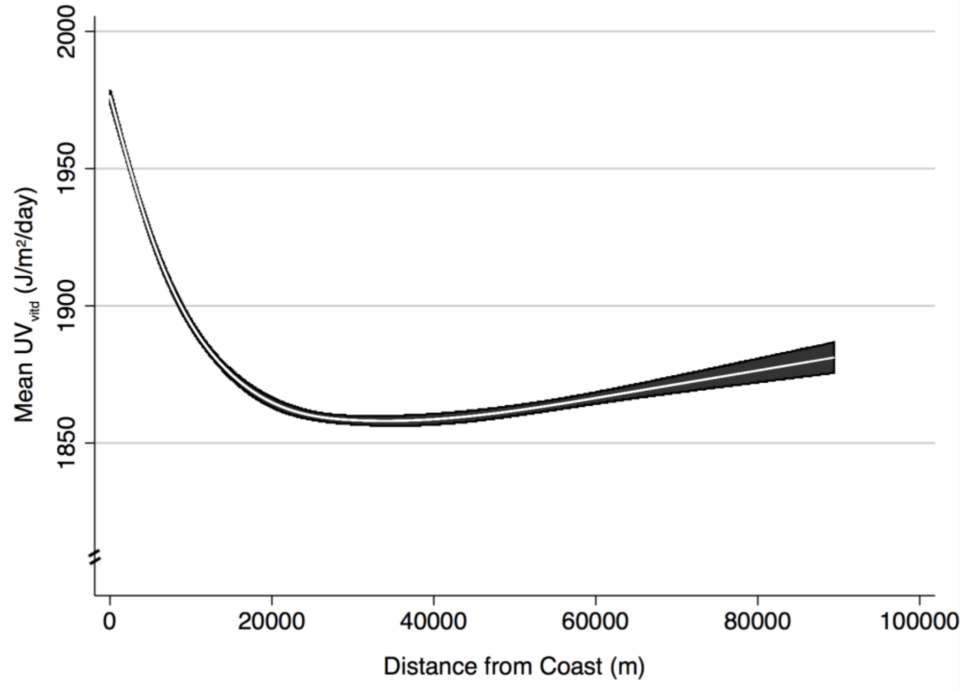
Table 2: The relationship between UV_{vitd} (J/m^2/day) and coastal proximity categories in Britain

	Regression Coefficient (95%CI)
Distance from Coast (km)	
>50	Ref
>20-50	-7.3 (-10.3- 4.4)**
>5-20	20.4 (17.5- 23.4) **
>1-5	85.5 (82.1- 88.8)**
<1	99.6 (96.1- 103.3)**
R^2	0.90
N	24,843

The results are presented with regression coefficients compared to the reference category and 95% confidence intervals in brackets; significance levels, * $p<0.05$ ** $p<0.01$

The linear regression analysis revealed that there was a significant relationship between distance from coast and mean annual UV_{vitd} in British settlements, with a 100J/m^2/day difference between >50km and <1km coastal categories (Table 2). There was a small but significant difference in UV_{vitd} between over 50 km away from coast and 20-50 km, $\beta=-7.3$ (95%CI -10.3 to -4.4). Thereafter there was a significant increase in the regression coefficient for each category of distance to coast; 99.6 (95%CI, 96.1 – 103.2) between the extreme categories. This relationship was modified by the latitude of the settlement (appendix A.2). A linear pattern was also observed in the 53-55ºN and 55-57ºN latitude band, however there was a reduction in the effect size. The trend in the 57ºN latitude band was weak due to the 0-1 km category having a significant negative coefficient, $\beta=-23.3$ (95%CI -45.1 to -1.4) in comparison to more than 50 km. The restricted cubic spline model of data for the whole of Britain highlighted the non-linear relationship between coastal proximity and mean $UV_{vitd.}$ The UV_{vitd} was reduced from the coast to approximately 40 km inland whereby there was a small and steady increase until 100 km (Figure 3).

Figure 3: The relationship between coastal proximity and UV_{vitd} in Britain.



The white line represents the regression coefficient; the black band represents the 95%CI.

There was significant variation in other climatic factors with regard to distance from coast (Table 3); between the extreme categories (<1 km and >50 km) temperature was significantly higher in coastal settlements (β=0.84°C, 95%CI 0.81- 0.87), as was precipitation (β =31.7mm, 95%CI 30.2 – 33.2), whereas cloud cover was lower (β= -1.62%, 95%CI -1.78 to 1.46).

Table 3: The relationship between coastal proximity categories and climatic factors in Britain

	Regression Coefficient (95%CI)		
	Temperature (°C)	Cloud Cover (%)	Precipitation (mm)
Distance from Coast (km)			
>50	Ref	Ref	Ref
>20-50	-0.02 (-0.04-0.01)	-1.32 (-1.45 to -1.20)**	10.3 (9.0 – 11.5)**
>5-20	0.32 (0.29-0.31)**	-1.95 (-2.10 to -1.82)**	15.0 (13.8 – 16.3)**
>1-5	0.69 (0.66-0.73)**	-2.22 (-2.36 to -2.07)**	14.8 (13.3 - 16.2)**

<1	0.84 (0.81-0.87)**	-1.63 (1.78 to -1.46)**	31.7 (30.2 -33.2)**
R^2	0.72	0.46	0.24
N	23,835	23,837	23,323

The multiple linear regression results between coastal proximity and climatic factors adjusted for latitude. The results are presented with regression coefficients compared to the reference category and 95% confidence intervals in brackets; significance levels, * $p<0.05$ ** $p<0.01$

3.2. Coastal Proximity and 25(OH)D

We found no discernible differences between coastal category groups and selected characteristics (Table 4).

Table 4: Selected Characteristics of 1958 Birth cohort members by residential proximity to coast categories

Characteristic	Variable	Coastal Category n (%)				
		>50 km	20-50 km	5-20 km	1-5 km	<1 km
Demographic and Lifestyle	Sex					
	• Female	1,483 (49)	1,132 (51)	698 (52)	489 (49)	209 (51)
	Social Class (from employment)					
	• I & II – Professional/Managerial	1,246 (41)	977 (44)	505 (39)	365 (37)	169 (41)
	• III- Skilled non-manual	627 (21)	433 (19)	299(22)	215 (22)	80 (19)
	• III- Skilled manual	553 (18)	381 (17)	256 (19)	191 (19)	84 (20)
	• IV & V- Partly skilled/Unskilled	452 (15)	362 (15)	227 (17)	175 (18)	64 (16)
	Smoking Status					
	• Current Smoker	665 (23)	483 (22)	308 (24)	264 (28)	109 (27)
Opportunities for vitamin D Synthesis	Summer Outdoor Activity					
	• Less than 30 mins	62 (2)	45 (2)	21 (0)	27 (2)	7 (2)
	• 30 mins to 1 hour	192 (7)	117 (6)	86 (7)	57 (6)	23 (6)
	• 1 hour to 2 hours	680 (25)	504 (25)	274 (22)	181 (20)	83 (22)
	• 3 to 4 hours	673 (25)	528 (26)	356 (29)	212 (24)	97 (26)
	• 4 hours or more	1,120 (41)	836 (41)	505 (41)	409 (46)	164 (43)
	Sunscreen Use					
	• Often	1,619 (59)	1,220 (60)	751 (60)	534 (60)	226 (60)
	• Sometimes	848 (31)	642 (31)	382 (31)	257 (29)	106 (28)
	• Rarely	196 (7)	108 (5)	72 (6)	61 (7)	31 (8)
	• Never	97 (4)	75 (4)	40 (3)	42 (5)	16 (4)
Factors relating to vitamin D Metabolism	Obesity (BMI >30)					
	• Yes	700 (24)	486 (22)	317 (24)	233 (24)	115 (28)
Vitamin D Diet	D2 or D3 Supplements					
	Yes	350 (12)	271(13)	124(10)	113(14)	46(12)
	Cod liver oil Supplements					
	Yes	470 (17)	368 (19)	172 (15)	152 (17)	63 (17)
	Oily fish Consumption					
	Yes	2535 (86)	1907 (88)	1127 (87)	837 (87)	344 (86)

Selected characteristics of participant from the 1958 Birth Cohort are presented in the table above. Numbers and percentages are presented

The unadjusted and adjusted model showed a significant increase in 25(OH)D level with increased proximity to coast with coefficients of 0.1 (95%CI 0.05-0.16) and 0.08 (95%CI 0.02-0.13) respectively between the most extreme categories (Table 5).

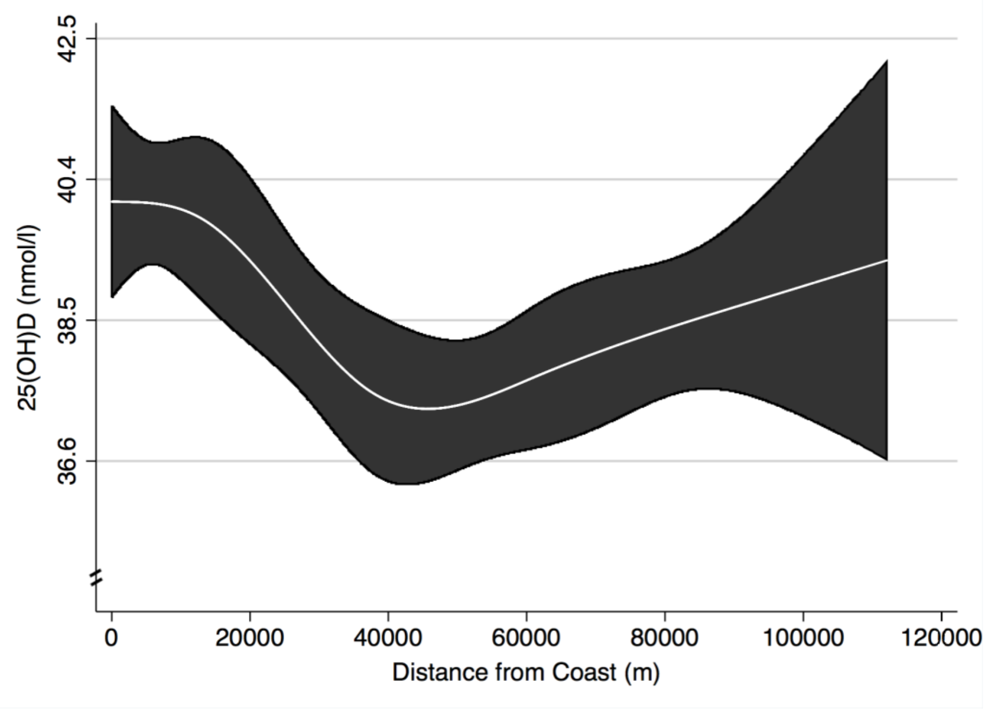
Table 5: The relationship between coastal proximity categories and 25(OH)D (nmol/l)

	Regression Coefficient (95%CI)	
	Model 1	Model 2
Distance from Coast (km)		
>50	Ref	Ref
>20-50	0.01 (-0.02 -0.04)	-0.01 (-0.04 to -0.02)
>5-20	0.06 (0.03 – 0.09)**	0.05 (0.01 – 0.08)*
>1-5	0.07 (0.03- 0.11)**	0.05 (0.01 -0.09)*
<1	0.1 (0.05 – 0.16)**	0.08 (0.03 -0.13)**
R^2	0.04	0.12
N	6,469	4,789

Model 1 is the unadjusted linear regression model. Model 2 is the adjusted model with sex, social class, smoking status, summer outdoor activity, sunscreen use, vitamin d supplementation, cod liver oil supplements and oily fish intake included. 25(OH)D has been log-transformed and standardised by month of measurement using a sine-cosine model. The results are presented with regression coefficients and 95% confidence intervals in brackets; significance levels, * p<0.05 ** p<0.01

There was no significant difference in 25(OH)D between over 50 km and 20-50 km residence. The below 1 km distance from coast category was the only category that was highly significant (p<0.01) in both models. The adjusted restricted cubic spline model illustrated the non-linear effect of coastal residence on 25(OH)D level with an approximately linear decrease from 0 to 45 km and a gradual trend in increase until 75 km (Figure 4). The difference in 25(OH)D between those closest to the coast and 45 km inland was 3.77 nmol/l. The relationship between distance to coast and vitamin D above 75 km was unclear due to large confidence intervals.

Figure 4: The relationship between coastal proximity (m) and 25(OH)D (nmol/l)

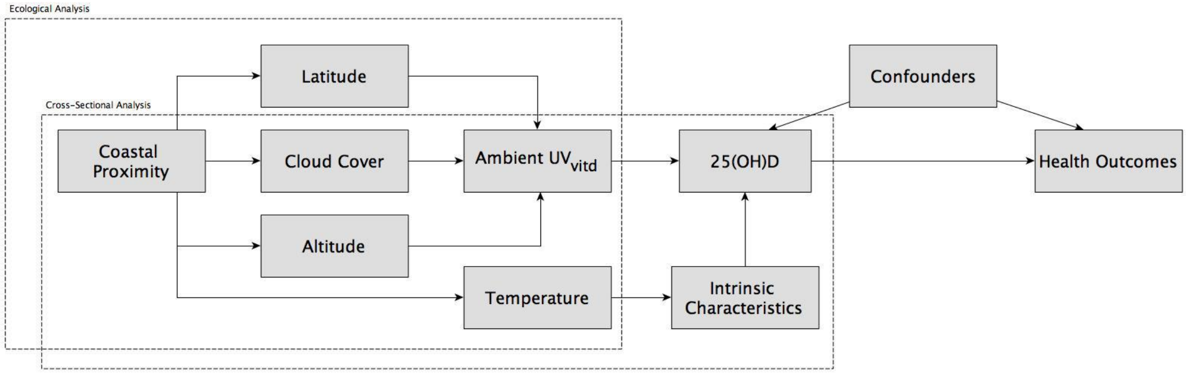


The white line represents the regression coefficient; the black band represents the 95%CI.

4. Discussion

We found that coastal areas have a climate favourable for vitamin D synthesis due to higher solar irradiance and temperature compared to further inland. These climatic factors are shown to associate with 25(OH)D level of residents of coastal areas; those living in coastal areas recorded on average a 4 nmol/l higher 25(OH)D level after accounting for several factors associated with vitamin D synthesis, metabolism and diet. We propose a directed acyclic graph presented in Figure 5 to describe the associations found in this study, which may explain one of the mechanisms by which coastal residents report better health outcomes than those who reside further inland. In contrast, heightened UVR at the coast can also cause higher risk of certain skin cancers such as squamous cell carcinoma, as shown in Sweden (Andersson et al. 2011). There may also be an interaction with other geographic risk factors. For example, the effect of coastal climate on allergen concentration could explain why those living further than 30 km from the coast were less likely to have several symptoms of wheezing (OR 0.90, CI 0.85-0.96) and tightness of chest (OR 0.92, CI 0.86-0.97) and less frequent asthma attacks (OR 0.93, CI 0.86-0.98) in an Italian multicentre survey (Zanolin et al., 2004).

Figure 5: Proposed directed acyclic graph of the relationship between proximity to coast and health outcomes



The two analyses have provided evidence for a potential effect of residential coastal proximity on health outcomes as presented in the directed acyclic graph. Coastal proximity is associated with UV$_{vitd}$ through cloud cover, which is modified by latitude and altitude of residence. Coastal proximity is associated with 25(OH)D through UV$_{vitd}$ although this is mediated by temperature and intrinsic characteristics. The relationship between 25(OH)D and health outcomes will only be valid after accounting for confounders, which are specific to the health outcome.

After adjusting for latitude the difference in UVR between the coastal categories can be explained by cloud cover and altitude. Stratospheric ozone can be discounted due to a similar rate of decrease being observed at measuring sites at Lerwick and Southern England since 1979 (5.8% and 4.8% respectively) (Smedley et al. 2012). It is therefore assumed that the effect of stratospheric ozone on annual UVR variation between regions of the UK is very low. Topographic forcing of clouds is the most probable explanation for the difference in UV$_{vitd}$, however this was only partly shown in our analysis. There was a reduction in cloud cover but this was seen in the other categories as well. It is proposed that cloud cover at midday when UV_{vitd} is at its peak could result in a higher mean annual UV_{vitd} however this may not be clear from average cloud cover data which included cloud conditions during the rest of the day. Finally, we observed a gradual increase in UV_{vitd} after 45 km from the coast which may be due to an increase in altitude (appendix A.3); altitude is shown to increase UVR due to a thinner atmosphere and a reduction of aerosols (Webb 2006), but this has uncertainty associated with it, probably due to the low numbers in this category (>45 km coastal distance) and complexity of the inland environment. A high altitude environment above 57ºN may explain the weak association between coastal proximity and UV_{vitd} in this latitude band.

There is approximately a 100 J/m^2/day difference in mean daily UV_{vitd} exposure and 0.8ºC difference in mean annual temperature between living within 0-1 km and around 50 km from the coast. Extrapolating data from an Australian study (Lucas et al. 2013), it was predicted that this could confer a difference of 4.5 nmol/L in 25(OH)D level (appendix B.1). We have shown that this effect is consistent in Britain with a 4.0 nmol/l difference detected between coastal residents and those living at around 50 km inland. The difference between the prediction and observed may be due to a younger sample used by Lucas et al.; younger adults have higher levels of 7-DHC (A. Webb 2006) and are therefore less likely to display variation in status due to increased capacity for synthesis, the primary route of vitamin D intake.

Coastal residence is associated with higher 25(OH)D in a study of middle aged Finnish men (Brock et al. 2010). After adjusting for several confounders including age, residential area, laboratory of 25(OH)D sub-study analysis, number of years having smoked, number of cigarettes per day, serum cholesterol and total dietary energy, those that lived in an area with sea coast had a significantly higher

25(OH)D level (β=6.4, $p<0.01$) (Brock et al. 2010), similar in range to the differences we found. A higher odds ratio for being in the over 25 nmol/l category was observed in both winter (OR,1.4; CI 1.0-2.0) and summer (OR, 1.9; CI, 1.2-2.9) for those living in coastal regions (Brock et al. 2010). We would expect that the difference between coastal and inland resident's 25(OH)D would mirror the seasonality of solar irradiance across the year as shown in a British sample (Webb et al. 2010). Thus as in Brock, the differences we have observed would be higher in summer and lower in winter.

Natural differences in ambient UV_{vitd} and their effect on vitamin D status can be modified by human behaviour. Our assumption that coastal populations are more likely to spend their time at the coast is demonstrated with data from Natural England's Monitor of Engagement with the Natural Environment (MENE) survey, whereby 51% of visits are by people who live within 5km of the coast (Natural England, 2011). Brock et al discuss the role of behavioural factors such as a lower propensity to wear sun protection and involvement in water sports (due to the high albedo of water and reduced clothing) (Brock et al. 2010). In contrast, we did not find any significant differences in factors relating to opportunities for vitamin D synthesis. Another possibility is that there is a higher intake of dietary vitamin D at the coast, however we found no support for this. It has been shown that regional and urban/rural differences only present small differences (e.g. 360 IU over a month between urban and rural) (Defra 2013) (appendix A.4). A homogenised regional diet due to transnational supermarkets could explain these findings; in 2011, the 11 largest supermarkets held 89% of the grocery market in the UK (Defra 2014). In comparison to diet, the effect of UVR is much greater with ¼ minimal erythemal dose to ¼ of the body being equivalent to 1000 IU (Holick 2001).

There were several strengths and limitations of the ecological analysis. The DLUA dataset is an appropriate way of understanding the ambient UV exposure of where people live as the dataset is able to capture settlements larger than a hamlet (i.e. several households). The analysis was enriched by the use of UV_{vitd} data, which is modelled to represent the wavelengths that are effective in vitamin D synthesis. There is significant debate on the pre-vitamin D synthesis action spectrum (Norval et al. 2009), however at the time of the data modelling this was the most appropriate weighting. This is the first time that a study has investigated the population level distribution of ambient UV_{vitd} in Britain. An assumption of the research is that 2002-2003 act as representative years in terms of UV radiation, although there is evidence that 2002 was less sunny and 2003 significantly more sunny than the mean 30 year average (Met Office 2014). We have therefore underestimated the year to year variation in the effect of coastal residence on 25(OH)D, however are confident that the effect would persist. Specific limitations of the current UVR data include oversampling at Northern latitudes due to the nature of the data collection (i.e. from a geostationary satellite). Further work is required using other UVR datasets to validate the current findings for subsequent years. Finally, UV_{vitd} at this resolution is not truly indicative of local conditions which may display a large variation due to features of the immediate environment (Webb & Engelsen 2006), for example urban areas are harder to quantify given the density of pollutants, building albedo and shading, factors which could not be elucidated in the current analysis.

The cross-sectional analysis had several strengths and weaknesses. The 25(OH)D data is from a large geographically dispersed sample, which has been standardised by the vitamin D external quality assessment scheme, allowing comparison with other data generated using different assays. The sample is middle-aged and Caucasian, which limits generalisability to the British population, although is also a strength as it negated the impact of ethnicity and age, which otherwise would have required a larger sample to observe differences. The biomedical sweep included several measures on intrinsic characteristics related to vitamin D intake, as shown to be associated with 25(OH)D in previous analyses (Hyppönen & Power 2007), which reduced the potential for confounding on these terms. However, there are unmeasured confounders including holidays abroad, sunbed use and clothing (% body exposure) and body position, which could not be accounted for in the analysis. There is also the possibility of residual confounding due to the broad categories used to assess a very sensitive reaction (e.g. small doses of sunshine at midday may produce large effects on 25(OH)D) (M. Bogh et al. 2011). The regression analyses did not violate assumptions on linearity, specification or multicollinearity; however there were issues with normality and homoscedasticity of errors, partly due to several outliers. Independence of errors was not tested formally however due to the wide variation of 25(OH)D levels at each spatial unit, it is proposed there would only be weak spatial autocorrelation. We log transformed the 25(OH)D variable which resulted in better model fit; however given that several assumptions were not met, results are presented with the acknowledgment that standard errors may be inflated, although this is unlikely to have impacted the key messages of the analysis.

5. Conclusion

Greater proximity to the coast was associated with an increase in solar irradiance as measured by UV_{vitd}. This was paralleled by an increase in 25(OH)D in participants in the 1958 Birth Cohort. Geographic location in Britain may influence biochemistry and health outcomes due to environmental factors. This can provide benefits in terms of vitamin D status but may also pose a risk due to higher skin cancer risk. We provide further evidence in support of the claim that coastal environments can provide opportunities for health and wellbeing.

References

Andersson, E.M., Paoli, J. & Wastensson, G., 2011. Incidence of cutaneous squamous cell carcinoma in coastal and inland areas of Western Sweden. *Cancer Epidemiology*, 35(6), pp.69–74.

Atherton, K., Fuller E., Shepherd P., Strachan D.P., and Power C., 2008. Loss and representativeness in a biomedical survey at age 45 years: 1958 British Birth Cohort. *Journal of Epidemiology and Community Health*, 62(3), pp.216–223.

Bauman, A., Smith, B., Stoker L., Bellew B and Booth M., 1999. Geographical influences upon physical activity participation: evidence of a 'coastal effect'. *Australian and New Zealand Journal of Public Health*, 23(3), pp.322–324.

Bauman A.E., Reis R.S., Sallis J.F., Wells J.C., Loos R.J., Martin BW., 2012. Correlates of physical activity: why are some people physically active and others not? The Lancet, 380(9838), pp.258–271.

Berry, D.J. Hesketh K., Power C., Hypponen E., 2011. Vitamin D status has a linear association with seasonal infections and lung function in British adults. *British Journal of Nutrition*, 106(9), pp.1433–1440.

Bogh, M., Schmedes, A.V. & Philipsen, P.A., 2011. Vitamin D production depends on ultraviolet-B dose but not on dose rate: A randomized controlled trial. Experimental Dermatology, 20, 14–18

Bogh, M.K., Schmedes, A.V., Philipsen, P.A., Thieden, E., and Wulf, H.C. 2009. Vitamin D production after UVB exposure depends on baseline vitamin D and total cholesterol but not on skin pigmentation. The Journal of investigative dermatology, 130(2), pp.546–553.

Brock, K.E., Graubard B.I., Fraser D.R., Weinstein S.J., Stolzenberg-Solomon R.Z, Lim U., Tangrea J.A., Virtamo J., Ke L., Snyder K., and Albanes D., 2010. Predictors of vitamin D biochemical status in a large sample of middle-aged male smokers in Finland. European Journal of Clinical Nutrition, 64(3), pp.280–288.

Buis, M., 2014. Maarten Buis: postrcspline. Available at: http://maartenbuis.nl/software/postrcspline.html [Accessed March 1, 2014].

Defra. 2013. Family Food Datasets. Available at: https://www.gov.uk/government/statistical-data-sets/family-food-datasets [Accessed May 15, 2014]

Defra. 2014. Food Statistics Pocketbook 2013: in year update. Available at: https://www.gov.uk/government/publications/food-statistics-pocketbook-2013 [Accessed June 1, 2014].

Garcion, E. Wion-Barbot N., Montero-Menei, C.N., Berger, F., and Wion, D., 2002. New clues about vitamin D functions in the nervous system. *Trends in endocrinology and metabolism: TEM*, 13(3), pp.100–105.

Harrell, F.E., 2001. Regression modeling strategies: with applications to linear models, logistic regression, and survival analysis. 1st ed., Springer

Hartig, T., Evans, G.W., Jamner, L.D, Davis, D.S, and Gärling, T., 2003. Tracking restoration in natural and urban field settings. *Journal of Environmental Psychology*, 23(2), pp.109–123.

Holick, 2002. Sunlight,“D”ilemma: risk of skin cancer or bone disease and muscle weakness. *Lancet*, vol. 357 (9249), pp.4–6.

Holick, M., 2004. Vitamin D: importance in the prevention of cancers, type 1 diabetes, heart disease, and osteoporosis. *American Journal of Clinical Nutrition*. pp. 362–371.

Holick, M.F., 2007. Vitamin D deficiency. *The New England journal of medicine*, 357(3), pp.266–281.

Hughes, A.M., Lucas, R.M, Ponsonby, A.L, Chapman, C., Coulthard, A., Dear, K., Dwyer, T., Kilpatrick, T.K., McMichael, A.J., Pender, M.P., Taylor, B.V., Valery, P., Van der Mei, I., and Williams, D., 2011. The role of latitude, ultraviolet radiation exposure and vitamin D in childhood asthma and hayfever: an Australian multicenter study. *Pediatric Allergy and Immunology*, 22(3), pp.327–333.

Hyppönen, E. & Power, C., 2007. Hypovitaminosis D in British adults at age 45 y: nationwide cohort study of dietary and lifestyle predictors. *The American journal of clinical nutrition*, 85(3), pp.860–868.

Llewellyn, D.J., Langa, K.M. & Lang, I.A., 2009. Serum 25-hydroxyvitamin D concentration and cognitive impairment. *Journal of geriatric psychiatry and neurology*, 22(3), pp.188–195.

Lucas, R.M., Ponsonby A.L, Dear K., Valery P.C., Taylor B., Van der Mei, I., McMichael, A.J, Pender, M.P, Chapman, C., Coulthard, C., Kilpatrick, T.J., Stankovich, J., Williams, D., and Dwyer, T., 2013. Vitamin D status: Multifactorial contribution of environment, genes and other factors in healthy Australian adults across a latitude gradient. *Journal of Steroid Biochemistry and Molecular Biology*, 136, pp.300–308.

MacLaughlin, J., Anderson, R.R. & Holick, M.F., 1982. Spectral character of sunlight modulates photosynthesis of previtamin D3 and its photoisomers in human skin. *Science*, 216(4549), pp.1001–1003.

Maddock, J., Berry, D.J., Geoffroy, M.C., Power, C., and Hyppönen, E., 2013a. Vitamin D and common mental disorders in mid-life: cross-sectional and prospective findings. *Clinical nutrition*, 32(5), pp.758–764.

Maddock, J., Geoffroy, M.C, Power, C., and Hyppönen, E., 2013b. 25-Hydroxyvitamin D and cognitive performance in mid-life. *British Journal of Nutrition*, pp.1–11.

McCurdy, T. & Graham, S.E., 2003. Using human activity data in exposure models: analysis of discriminating factors. *Journal of exposure analysis and* *environmental epidemiology*, 13(4), pp.294–317.

Met Office, 2014. *Met Office*, UKCP09. Available at: http://www.metoffice.gov.uk/climatechange/science/monitoring/ukcp09/ [Accessed June 6, 2013].

Natural England, 2011. Monitor of Engagement with the Natural Environment. Natural England, Sheffield, Annual Report from the 2010–11 survey.

Norval, M., Björn, L.O. & de Gruijl, F.R., 2009. Is the action spectrum for the UV-induced production of previtamin D3 in human skin correct? *Photochemical & Photobiological Sciences*.

Ordnance Survey, 2012. Meridian 2: User Guide and Technical Specification. pp.1–94. Available at: http://digimap.edina.ac.uk/webhelp/os/data_information/os_products/download_user_guides.htm#meridian.

Perry, M. & Hollis, D., 2005. The generation of monthly gridded datasets for a range of climatic variables over the UK. *International Journal of Climatology*, 25(8), pp.1041–1054.

Pope, S.J., Holick, M.F, Mackin, S., and Godar, D.E., 2008. Action spectrum conversion factors that change erythemally weighted to previtamin D3-weighted UV doses. *Photochemistry and Photobiology*, 84(5), pp.1277–1283.

Power, C., 2005. Cohort profile: 1958 British birth cohort (National Child Development Study). *International journal of epidemiology*, 35(1), pp.34–41.

Smedley, A.R.D., Rimmer J.S, Moore D., Toumi R., and Webb A.R, 2012. Total ozone and surface UV trends in the United Kingdom: 1979-2008. *International Journal of Climatology*, 32(3), pp.338–346.

Thompson Coon, J., Boddy, K., Stein, K, Whear, R, Barton, J, and Depledge, M.H., 2011. Does Participating in Physical Activity in Outdoor Natural Environments Have a Greater Effect on Physical and Mental Wellbeing than Physical Activity Indoors? A Systematic Review. *Environmental Science & Technology*, 45(5), pp.1761–1772.

Tian, X.Q., Chen, C., Matsuoka, L.Y., Wortsman, J., and Holick, M.F., 1993. Kinetic and thermodynamic studies of the conversion of previtamin D3 to vitamin D3 in human skin. *The Journal of biological chemistry*, 268(20), pp.14888–14892.

Verdebout, J., 2004. A European satellite-derived UV climatology available for impact studies. *Radiation protection dosimetry*, 111(4), pp.407–411.

Warburton, D.E.R., 2006. Health benefits of physical activity: the evidence. *Canadian Medical Association Journal*, 174(6), pp.801–809.

Webb, A., 2006. Who, what, where and when - influences on cutaneous vitamin D synthesis. *Progress in Biophysics & Molecular Biology*. pp. 17–25.

Webb, A.R. & Engelsen, O., 2006. Calculated ultraviolet exposure levels for a healthy vitamin D status. *Photochemistry and Photobiology*, 82(6), pp.1697–1703.

Webb, A.R., Kift R., Durkin M.T., O'Brien S.J, Vail A., Berry J.L, and Rhodes L.E., 2010. The role of sunlight exposure in determining the vitamin D status of the U.K. white adult population. *British Journal of Dermatology*, 163(5), pp.1050–1055.

Wheeler, B.W., White M, Stahl-Timmins W., and Depledge M.H, 2012. Does living by the coast improve health and wellbeing?. *Health & Place*, 18(5), pp.1198–1201.

White, M.P., Alcock I., Wheeler B.W., and Depledge M.H., 2013a. Coastal proximity, health and well-being: Results from a longitudinal panel survey. Health & Place, 23(C), pp.97–103.

White, M.P., Pahl, S. Ashbullby, K.J., Herbert, S.and Depledge, M.H., 2013b. Feelings of restoration from recent nature visits. Journal of Environmental Psychology, 35, 40-51.

White, M.P., Wheeler, B., Herbert, S., Alcock, I. and Depledge, M.H. (Unpublished results). Coastal proximity and physical activity: Is the coast an underappreciated public health resource. Manuscript submitted for publication.

Wortsman, J., Matsuoka L.Y., Chen T.C., Lu Z., and Holick M.F., 2000. Decreased bioavailability of vitamin D in obesity. The American journal of clinical nutrition, 72(3), pp.690–693.

Appendices

Appendix A.1: 1958 Birth Cohort covariates

Synthesis	Metabolism	Diet	Demographic/Lifestyle
Outdoor Activity in Summer: How long per day do/did you usually spend outdoors in Summer?	Obesity: $\mathrm{BMI} = \frac{\text{mass (kg)}}{\text{height2}}$ Obesity = BMI>30, as per World Health Organisation definition	Vitamin D supplementation (single vitamin or as part of multi-vitamin): What do these supplements contain (no. of codes); Vitamin D	Sex: Determined at birth
Sunscreen use: In sunny weather, do you protect your skin from the sun		Cod liver oil Supplementation: How often have you taken supplements of cod liver oil or fish oil?	Social Class: Derived from Occupation information at age 42 using Registrar General's classification system
		Oily fish consumption: How often do you eat other fish?	Smoking: Derived from information at age 42

Appendix A.2: The relationship between UV_{vitd} (J/m^2/day) and coastal proximity categories in Britain by latitude band

	Regression Coefficient (95%CI)				
	<51	51-53	53-55	55-57	>57
>50 km	- -	Ref -	Ref -	Ref -	Ref -
20-50 km	Ref -	30.2 (25.9 – 33.5)**	-41.7 (-55.6 to -27.8)**	-11.3 (-31.1 – 8.4)	12.3 (-10.2 – 34.7)
5-20 km	41.8 (22.5 – 47.6)**	64.5 (59.8 – 69.3)**	-0.5 (-14.4 - 13.4)**	4.9 (-14.7 – 24.4)	32.9 (10.8 – 55.1)**
1-5 km	120.0 (107.0 -132.9)**	117.6 (111.8 – 123.4)**	49.6 (35.2 – 64.1)**	63.8 (43.8 – 83.9)**	47.0 (24.6 -69.3)**
<1 km	143.7 (130.2 -157.1)**	138.3 (130.4 – 146.2)**	54.4 (38.8 -70.0)**	80.0 (60.2 – 99.8)**	-23.3 (-45.1 to -1.4)*
R^2	0.33	0.19	0.15	0.24	0.14
N	2,400	10,589	5,071	3,323	2,855

The linear regression results stratified by latitude bands are presented in the table above. The results are presented with regression coefficients compared to the reference category and 95% confidence intervals in brackets; significance levels, * $p<0.05$ ** $p<0.01$

Appendix A.3: Altitude by coastal category

	Regression coefficient (95%CI)
>50km	Ref -
20-50 km	-9.6 (-12.3 to -6.8)**
5-20 km	-48.6 (-51.4 to 45.8)**
1-5 km	-86.3 (-89.3 to -83.1)**
<1 km	-115.6 (-119.0 to -112.3)**
R^2	0.27
N	23,819

The linear regression model results on the relationship between altitude and coastal proximity categories are presented in the table. The results are presented with regression coefficients and 95% confidence intervals in brackets; significance levels, * p<0.05 ** p<0.01

Appendix A.4: Geographical differences in Dietary vitamin D

		Year						
Description	**Units**	**06**	**07**	**08**	**09**	**10**	**11**	**12**
Urban	µg	2.83	2.76	2.64	2.65	2.71	2.72	2.68
Rural	µg	2.91	3.03	2.91	3.04	3.00	3.00	3.02
Daily difference	µg	0.08	0.27	0.27	0.39	0.29	0.29	0.35
Daily difference	IU	3	10.7	10.7	15.6	11.7	11.5	13.8
Monthly difference	IU	90	321	321	468	351	345	414

		Year											
Description	**Units**	**01-02**	**02-03**	**03-04**	**04-05**	**05-06**	**06**	**07**	**08**	**09**	**10**	**11**	**12**
North East	µg	3.0	3.2	3.0	3.0	3.0	3.1	2.7	2.3	2.7	2.8	2.5	2.6
North West	µg	3.4	3.2	3.1	3.0	3.0	2.8	2.9	2.8	2.8	2.6	2.8	2.8
Yorkshire	µg	3.2	3.4	2.8	2.7	2.9	3.0	2.7	2.7	2.7	2.7	2.6	2.7
E. Midlands	µg	3.4	3.3	3.1	3.2	3.3	3.1	2.9	2.8	2.9	3.0	2.9	2.9
W. Midlands	µg	3.3	3.4	3.0	2.9	2.9	3.0	2.9	2.7	2.9	2.7	2.8	2.8
East	µg	3.6	3.3	3.2	3.0	3.0	2.9	2.9	2.8	2.9	3.1	3.0	2.9
London	µg	3.1	3.0	2.5	2.5	2.5	2.7	2.5	2.4	2.4	2.5	2.4	2.4
South East	µg	3.3	3.3	2.8	3.0	2.9	2.9	2.9	2.7	2.7	2.8	2.8	2.8
South West	µg	3.4	3.5	3.1	2.9	3.0	2.8	3.1	2.9	2.8	2.9	3.1	2.9
Daily Mean	µg	3.3	3.3	3.0	2.9	2.9	2.9	2.8	2.7	2.7	2.8	2.8	2.8
Daily SD	µg	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Daily SD	IU	7.2	6.6	8.8	7.9	7.5	5.5	6.7	8.0	6.8	7.7	8.6	6.4
Monthly SD	IU	216	198	264	237	225	165	201	240	204	231	258	192

Data above is from The National Diet and Nutrition Survey for British households; conversions made using the formula of 1 µg = 40 IU, monthly estimates are generated by multiplying by 30; SD, standard deviation

Appendix B.1: Ambient UV- 25(OH)D Calculations

1. UV_{ery} and temperature relationship with 25(OH)D (Lucas et al. 2013)

100 J/m^2 UV_{ery}= 0.52 nmol/l

0.8 ºC =3.75 nmol/l

2. Action spectrum conversion factors for UV_{ery} to UV_{vitd} (Pope et al. 2008)

100 J/m^2 UV_{ery}=74.625 J/m^2 UV_{vitd}

100 J/m^2 UV_{vitd}=134 J/m^2 UV_{ery}

Therefore 0.70 nmol/l difference due to UV

And 3.75 difference due to temperature

Total difference 4.5nmol/l

*Action spectrum conversion factor using average ozone levels for 50ºN and 55ºN latitude for all seasons=0. 74625 (Pope et al. 2008)

The estimated difference between the extreme coastal categories using previous published work on the relationship between ambient UVR and 25(OH)D is presented in the calculations above.

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